

DARK BARYONS IN THE UNIVERSE: THE QUEST GOES ON

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Abstract. We show that the high local baryonic fraction, $M_{bar} \sim 1/3 M_{tot}$, found in groups and clusters of galaxies does not reconcile the observed cosmological baryon density with the standard Big-Bang prediction. Taking into account recent measurements on the hot-gas content and temperature functions of clusters and groups, we get $\Omega_{gas}^{cg} = 2.3 \times 10^{-3} h_{50}^{-1.5} \simeq 4\% \Omega_{BBN}$. Including the contributions of galaxies and of (local) Ly α clouds we estimate $\Omega_{bar} \sim (4 - 6) \times 10^{-3} \lesssim 10\% \Omega_{BBN}$ as the amount of detected baryons. The great majority of the synthesised atoms are still to be discovered. We propose to relate the impressive presence of the hot gas component in clusters with the very low, mass-dependent efficiency of the process of galaxy formation in making stars from the primordial gas.

Introduction: The Baryon Overabundance in Clusters.

In a previous paper (Persic & Salucci 1992, hereafter PS92) we computed the cosmological density of the baryonic matter, Ω_{bar} , by means of an inventory of the stellar and gaseous content of galaxies, groups, and clusters (see also Bristow & Phillips 1994). The value we found, $\Omega_{bar} \simeq 3_{-2}^{+1} \times 10^{-3}$, implies that most of the cosmologically synthesised baryons do not reside in luminous structures but are disguised elsewhere in some invisible form. The above estimate relies on accurate dynamical methods able to derive the amount of luminous matter in the various cosmic structures. However, as far as groups and clusters of galaxies are concerned, their gas content

$$\Omega_{bar}^{cg} = \frac{1}{\rho_c} \int_{M_{gas}^{min}}^{M_{gas}^{max}} n(M_{gas}) M_{gas} dM_{gas}, \quad (1)$$

which accounts for virtually the whole baryonic content of these systems, was computed by: (a) a linear extrapolation of the inner IGM mass profiles out to the Abell radius, R_A ; and (b) assuming that groups have the same gas-mass function of clusters extrapolated to lower masses/temperatures. The value obtained, $\Omega_{bar}^{cg} = 1.5 \times 10^{-3} h_{50}^{-1.5}$, was therefore somewhat uncertain, although definitely much smaller than the standard Big Bang Nucleosynthesis (hereafter BBN) prediction $\Omega_{BBN} \simeq 0.06 h_{50}^{-2}$. In the past two years ROSAT and ASCA have mapped, in several clusters and groups, the density and temperature profiles of the intracluster (IC) gas out to $\sim R_A$ (e.g., Lubin et al. 1995), allowing the main structural properties of these structures to be established. A roughly spherical gaseous halo, most likely in thermal equilibrium and showing small temperature gradients (i.e. with $T(r) \sim const$), surrounds virtually every cluster and group. The space density is obtained by deprojecting the surface brightness of the emitting gas $I(r) \propto [1 + (\frac{r}{r_x})^2]^{-3\beta+1/2}$ (Cavaliere & Fusco-Femiano 1976) to obtain: $\rho_X(r) \propto [1 + (\frac{r}{r_x})^2]^{-3\beta/2}$; the gravitating mass density is obtained by means of the hydrodynamic equilibrium equation (see Sarazin 1986): since $\beta \simeq 2/3$ (e.g., Davis, Forman & Jones 1995), it follows $\rho(r) \propto [3 - (\frac{r}{r_x})^2]/[1 + (\frac{r}{r_x})^2]^2$. Therefore, the dark-to-baryonic density ratio decreases with radius so that in most clusters and groups the visible-to-dark mass ratio at $\sim R_A$ exceeds the cosmological limit Ω_{BBN}/Ω (unless Ω is low) (e.g.: David et al. 1995; Dell’Antonio, Geller & Fabricant 1995; Pildis, Bregman & Evrard 1995). In this paper we investigate whether such a high fraction is relevant for the quest of baryonic matter launched by PS92: can the IC gas, once properly taken into account, remove the need for baryonic dark matter (i.e., is $\Omega_{bar}^{cg} \simeq \Omega_{BBN}$)?

The main aim of this paper is to re-estimate Ω_{bar}^{cg} by means of the actual cluster (and group) gas masses and temperature functions, and to evaluate Ω_{bar} using also recent work on galaxy structure. A second aim is to explore a way out from the "baryon catastrophe" in clusters, by showing how their high baryonic fraction may be a consequence of a tight link between the two baryonic components of clusters, i.e. the gas and the galaxies.

A value of Hubble constant of 50 km s^{-1} is assumed throughout the paper.

The Determination of Ω_{bar}^{cg}

In terms of the cluster temperature T we have:

$$\Omega_{bar}^{cg} = \frac{1}{\rho_c} \int_{T_{min}}^{T_{max}} n(T) M_{gas}(T) dT. \quad (2)$$

Let us now examine each of these functions in turn.

- *Temperature Function.* Both clusters and groups are represented by a single temperature function:

$$n(T) dT = 2 \times 10^{-4} T^{-4.7} dT \text{ Mpc}^{-3}. \quad (3)$$

with T in keV (see Henry & Arnaud 1991, Henry et al. 1995). Notice that for clusters ($T > 3$ keV) eq.(3) is in substantial agreement with the Schechter-like function of Edge et al. (1990) used in PS92, while for groups ($T < 3$ keV) eq.(3) increases with decreasing temperature faster than the extrapolation of Edge et al. (1992) used in PS92.

- *Gas Mass–Temperature Relation.* In Appendix A we show that the gas content of clusters and groups relates with other structure properties; in particular:

$$M_{gas} = 8 \times 10^{12} T^{1.2} M_{\odot} \quad T \geq 3 \text{ keV} \quad (4a)$$

$$M_{gas} = 2 \times 10^{12} T^{2.5} M_{\odot} \quad T < 3 \text{ keV} \quad (4b)$$

The temperatures and the gas masses range, respectively, between $1 \text{ keV} < kT < 10 \text{ keV}$ and $10^{12} M_{\odot} < M_{gas} < 5 \times 10^{13} M_{\odot}$. Therefore, from eqs.(2),(3),(4) we obtain:

$$\Omega_{gas}^{cg} = 2.3 \times 10^{-3} h_{50}^{-1.5} \simeq 3\% \Omega_{BBN}, \quad (5)$$

i.e. 50% bigger than the PS92 estimate. This increase reflects the larger number density of ROSAT groups with respect to that implied by the temperature function adopted in PS92.

Thus, clusters and groups, being rare events, contribute very little to the present-day baryonic density, in spite of their high baryonic fraction. Structures with $kT \lesssim 1$ keV (such as galaxies, binaries, triplets, and compact groups) have a negligible gas content.

The Estimate of Ω_{bar} .

- *Galaxies.* We estimate the baryon content of E/S0 and spiral galaxies as in PS92:

$$\Omega_{bar}^{E,S} = \frac{1}{\rho_c} \int_{L_{max}}^{L_{min}} \left(\frac{M}{L} \right)_*^{E,S} \Phi^{E,S}(L) L dL. \quad (6)$$

We get (see Appendix B):

$$\Omega_{bar}^{gal} = \Omega_{bar}^E + \Omega_{bar}^S = 2 \times 10^{-3}, \quad (7)$$

in good agreement with PS92 and with Bristow & Phillips (1994). Remarkably, spirals and ellipticals contribute the same cosmological stellar mass density.

- *Ly α Clouds.* HST observations have revealed that the most numerous structures in the universe belong to a population of absorbing clouds of ~ 100 kpc radius and $\sim 10^9 M_{\odot}$: although their actual number density and physical properties are uncertain, their contribution to Ω_{bar} may be comparable with Ω_{bar}^{gal} (Shull, Stocke & Penton 1995).

We then estimate:

$$\Omega_{bar} = (2_{-0.5}^{+0.3} + 2_{-1}^{+0.5} h_{50}^{-1.5} + 2_{-2}^{+1}) \times 10^{-3} = (4 - 6) \times 10^{-3} \lesssim 10\% \Omega_{BBN}. \quad (8)$$

Discussion

We propose that the large amount of hot gas in clusters is the signature of the inefficiency of the process of disk/spheroid formation in transforming the primordial material into stars. The N_{gal} member galaxies in a cluster are distributed with luminosity according to a Schechter-type function:

$$\phi(L) dL \propto L^{-\alpha} e^{-L/L_*} dL, \quad (9)$$

with $\alpha \sim 2$ (e.g., De Propris et al. 1995). Given the definition of n_{rc} , the number of galaxies defining the Abell richness class (Abell 1958), we find $N_{gal} \sim 100 n_{rc}$. Then, since

$$n_{rc} = 10 \times T^{1.2} \quad (10)$$

(see Fig.1), we get:

Figure 1. The relation between Abell richness class and temperature (see Girardi et al. 1995)

$$M_{gas} \simeq 10^{10} M_{\odot} \times N_{gal}. \quad (11)$$

Eq.(11) suggests that in clusters the total amount of gas per member galaxy is independent of other cluster properties, and resembles a universal constant. In Persic, Salucci & Stel (1995; hereafter PSS95) we have shown that spiral proto-halos with pre-virialization gas-to-dark mass ratio Ω_{BBN}/Ω turn only a fraction

$$f = 0.65 (L/L_*)^{-0.6} \quad (12)$$

of their original baryon content into stars. Ellipticals show a similar behaviour (Bertola et al. 1993). Therefore, the amount of baryonic material left unused by the process of forming the disks and spheroids of the N_{gal} cluster galaxies is:

$$0.06 \int M_*(L) [1 - f(L)] \phi(L) dL = 10^{10} M_{\odot} \times N_{gal}, \quad (13)$$

where $M_*(L)$ is the stellar mass of a galaxy of luminosity L (see PSS95 and Bertola et al. 1993). This amount is comparable with the mass of the IC gas given by eq.(11): most of the IC medium has never been processed by stars, in agreement with cluster chemical abundances that independently imply that a large fraction of the ICM is primordial (Gibson & Matteucci 1995).

We suggest the following scenario: clusters switch on the ionised gas, unused in the disk/spheroid formation in cluster environment, by providing the (gravitational) potential needed to heat this medium up to the ambient virial temperature (~ 5 keV). The gas left over in the formation of field galaxies, on the other hand, wanders invisible in the cosmic void.

Conclusions

Of all the atoms synthesised in the Big Bang:

- 3% $\frac{0.06 h_{50}^{-2}}{\Omega_{BBN}}$ are locked up in stars;
- 4% $\frac{0.06 h_{50}^{-2}}{\Omega_{BBN}}$ form the ICM;
- 3% $\frac{0.06 h_{50}^{-2}}{\Omega_{BBN}}$ form the local population of Ly α clouds,

so that, we still have to discover about $(100 - 10 \times \frac{0.06 h_{50}^{-2}}{\Omega_{BBN}})\%$ of the primordially synthesised baryons. Let us notice that also in the light of a low baryon density, $\Omega_{BBN} \simeq 2.5 \times 10^{-2} h_{50}^{-2}$ (see Hogan 1995), the fraction of missing baryons is still $\gtrsim 50\%$.

Where are they? We suggest one or more of the following:

- *Diffuse Ionised IGM*. It naturally fits into the proposed scenario of primordial gas leftover from galaxy formation and remaining unseen if spread out in the field.
- *Halo Jupiters*. The detection of MACHOs in the Galactic halo (Alcock et al. 1995) may have revealed some baryonic dark matter, in the form of substellar objects as allowed by the *local* dynamical M/L ratios in spiral galaxies (PSS95).
- *Faint Galaxies*. A large population of low-surface-brightness dwarfs, detected at low flux limits, $B \sim 24.0$ (Driver et al. 1994), are missing from the much brighter samples used to derive galaxy LFs (see McGaugh 1995), and may contain a cosmologically relevant amount of baryons.

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APPENDIX A

In rich clusters, the dynamical mass and the gas mass are related by:

$$M_{gas} = 0.13 G^{-1} \sigma^2 R_A \quad (A1)$$

(see Lubin et al. 1995), with σ the line-of-sight velocity dispersion of the galaxies. By means of the well-known σ - T relationship:

$$\sigma = 340 T^{0.6} \text{ km s}^{-1} \quad (A2)$$

(see Girardi et al. 1995), we get eq.(4a). Using recent data, we plot the M_{gas} - T data also for a number of poor clusters and groups (see Fig.2), down to 1 keV, whose fit is shown in eq.(4b).

Figure 2. The gas mass versus temperature relation. The flatter portion of the curve is the relationship for clusters given by Lubin et al. (1995). The steepest part is our fit for the poor clusters and loose groups (with data from Dell'Antonio et al. 1995). (Compact groups have a significantly lower gas content, see Pildis et al. 1995.)

APPENDIX B

The luminosity functions of galaxies take the usual Schechter form $h = 1/2$):

$$\phi(L) dL = \phi_* \left(\frac{L}{L_*} \right)^{-\alpha} e^{-L/L_*} \frac{dL}{L_*}. \quad (B1)$$

The B -band LF parameters are shown in Table 1. The B -band stellar $(M/L)_*$ ratios scale with luminosity as

$$\left(\frac{M_*}{L} \right)_{E/S0} = 4 \left(\frac{L}{L_*} \right)^{0.35} \quad (B2)$$

$$\left(\frac{M_*}{L} \right)_S = 2 \times \text{dexp} \left[0.35 \log \left(\frac{L}{L_*} \right) - 0.75 \log^2 \left(\frac{L}{L_*} \right) \right], \quad (B3)$$

for elliptical and spiral galaxies, respectively (see van der Marel 1991 and PSS95, respectively). We follow the PS92 procedure. Notice that here we adopt: (1) the luminosity function for ellipticals as derived from a recent analysis of several cumulative LFs (Franceschini et al. 1995); and (2) the spiral disks' M/L ratios as derived from mass modelling of about 1100 rotation curves (PSS95). Notice that in both cases there is no substantial difference from the functions adopted in PS92.

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